NASA/TM—2005–213846

International Space Station Bacteria Filter Element Service Life Evaluation

J.L. Perry
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

April 2005

The NASA STI Program Office…in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results…even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076–1320
  301–621–0390

NASA/TM—2005–213846

International Space Station Bacteria Filter Element Service Life Evaluation

J.L. Perry
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

National Aeronautics and
Space Administration

Marshall Space Flight Center • MSFC, Alabama 35812

April 2005

Acknowledgments

Dean Thompson, The Boeing Company, who coordinated the return of the bacteria filter elements from the *International Space Station* and evaluated the benefits associated with extending their service life, contributed significantly to this effort. Roger von Jouanne and Edward Turner, also of The Boeing Company, provided technical review and guidance for the testing effort and report preparation. Charles Cooper, Micro Craft, and Ken Frederick, NASA, developed the test stand and data acquisition system as well as assisted with testing. Kristin Medley, NASA, assisted with test requirement development and testing.

TRADEMARKS

Available from:

NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076–1320
301–621–0390

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703–487–4650

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND SYMBOLS

BFE	bacteria filter elements
HEPA	high-efficiency particulate air
H_2O	water
ISS	*International Space Station*
PM	particulate matter
THC	temperature and humidity control
USOS	U.S. On-orbit Segment

TECHNICAL MEMORANDUM

INTERNATIONAL SPACE STATION BACTERIA FILTER ELEMENT SERVICE LIFE EVALUATION

1. INTRODUCTION

Airborne particulate matter (PM) in the *International Space Station's* (*ISS*'s) cabin atmosphere can have effects on both the crew and equipment. Suspended PM may irritate the crew members' respiratory tract and foul cabin ventilation systems. The *ISS* employs atmospheric filtration to minimize the risks presented to crew health and equipment operations by suspended PM.

1.1 Particulate Matter Design Considerations

The design approach for controlling suspended PM in the *ISS's* cabin is similar to that employed for trace chemical contaminant control. Like trace contaminant control, designing for PM control considers and tries to find a balance between performance, power consumption, and maintainability.[1] The most important design parameters for PM filtration are nominal filtration efficiency and filter element pressure drop. To achieve the most effective design solution, the selected filter media must provide high single-pass efficiency for the smallest particle size possible while maintaining a characteristically low pressure drop. High-efficiency particulate air (HEPA) filtration media was selected for the *ISS* and configured within the bacteria filter elements (BFEs) to minimize pressure drop and power consumption associated with filtering the cabin atmosphere.

While active filtration is needed, passive means are also employed before flight to minimize PM generation sources. Key to passive control is materials selection and control. Construction materials used in the *ISS* cabin are screened to ensure that they are nonfriable, which means they do not easily crumble or slough PM. Beyond minimizing particulate generation from materials of construction, the remainder of the PM generation load is highly dependent upon the crew. Most PM generated in the cabin originates from the crew in the form of skin cells, body hair, clothing fibers, and many other sources associated with human activities.

1.1.1 Allowable Cabin Air Particulate Matter Loading

A NASA-commissioned expert panel recommended PM loading based on human health considerations. This panel recommended a total suspended PM concentration of 0.4 mg/m^3 for the particles up to 100 μm in diameter with the total concentration split between two size ranges: 0.2 mg/m^3 for particles <10 μm in diameter and 0.2 mg/m^3 for particles ranging from 10 μm to 100 μm in diameter.[2]

The *ISS* program adopted a more conservative requirement that includes both an allowable cabin concentration and a point source generation rate. For this requirement, 0.05 mg/m^3 of PM ranging in size from 0.5 μm to 100 μm with periodic peaks to 1 mg/m^3 are allowed. The daily average, however, must be below the 0.05 mg/m^3 concentration. The total particulate generation specified for design is 1.4×10^6 particles/min. Developmental testing and engineering analyses based on this requirement indicate a 1-yr BFE service interval.

Comparatively, the *ISS* suspended PM requirement is identical to the requirement for PM loading defined by Federal Standard 209, Revision E, for a class 100,000 clean room. This requirement is ≈4 times lower than the maximum recommended to maintain crew health. Because significant conservatism is evident when comparing the requirement to that recommended to maintain human health, the first set of BFEs that were deployed on board the *ISS* were evaluated postflight to determine the actual rate of pressure drop increase and, if appropriate, to revise the service life.

1.1.2 Filter Element Design

To remove PM from the cabin atmosphere, the U.S. On-orbit Segment (USOS) uses a total of 13 BFEs located in the ventilation system as of *ISS* assembly flight 7A; 6 in the U.S. Laboratory (Destiny), 4 in node 1 (Unity), and 3 in the airlock (Quest). An overview of the USOS temperature and humidity control (THC) system, including the BFE location in each module, is found in reference 3. As designed, 100 percent of the cabin air entering the THC system in each module passes through the BFEs. Cabin latent and sensible heat loads dictate the process airflow rate through the ventilation system and, therefore, the BFEs, which makes the PM removal capacity flow limited with respect to generation rate. Process air flow through the BFEs does vary from module to module to maintain optimum cabin ventilation characteristics. Therefore, the flow through the BFEs in Destiny is normally about 113 m^3/hr (66.7 ft^3/min or cfm), while those in Unity and Quest may experience approximately 127 m^3/hr (75 cfm) and 85 m^3/hr (50 cfm), respectively.

Each BFE consists of pleated borosilicate HEPA media containing 0.3-μm pores mounted in a rectangular aluminum frame. Each BFE slides into a housing that acts as the interface to the ventilation system. Figure 1 shows a typical BFE. The filter media is rated at 99.97-percent efficiency for 0.3-μm-diameter particles. Pleats maximize the cross-sectional area leading to lower pressure drop. A 20-mesh (0.84-mm clear opening) prescreen on the filter's face captures lint and large debris that may excessively load the HEPA media. Figure 2 shows the BFE's HEPA media and prescreen.

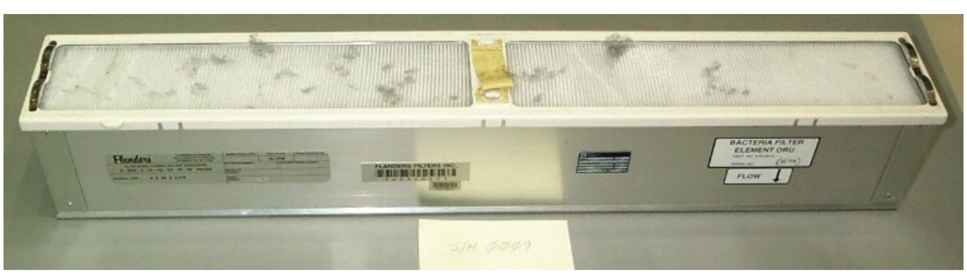

Figure 1. Typical bacteria filter element.

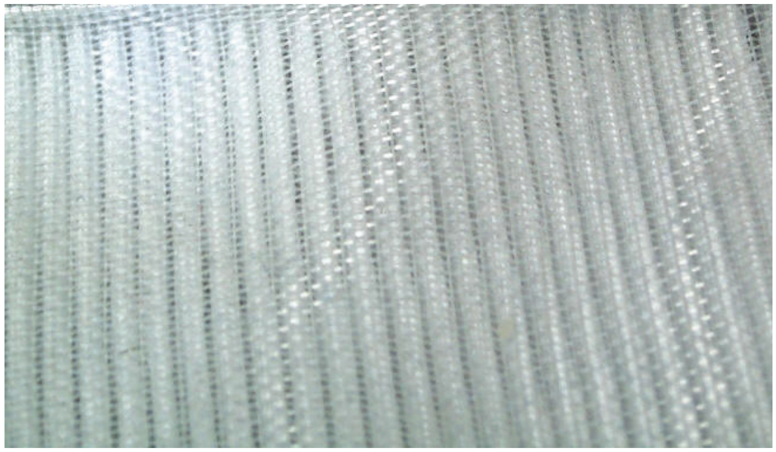

Figure 2. BFE media showing pleats and prescreen.

The crew periodically removes the lint and large debris from the filter face as part of the in-flight preventive maintenance program. Because lint buildup contributes significantly to overall pressure drop, this preventive maintenance helps manage the rising rate of pressure drop. According to design specification, a clean BFE is designed to have no more than 82.2 Pa (0.33 in water (H_2O)) pressure drop at 113 m^3/hr (66.7 ft^3/min) flow rate. At the end-of-life pressure drop of 124 Pa (0.5 in H_2O), each filter must be able to load with 32 g of PM.

2. AIRBORNE PARTICULATE MATTER IN SPACECRAFT

2.1 STS–32 Flight Data

Experiments to quantify the in-flight PM loading in a spacecraft cabin are rarely conducted. Such an experiment was conducted during shuttle mission STS–32 when instruments for measuring PM size distribution were flown.[4] Experimental results showed a total mass concentration a little more than one-half the *ISS* design specification—0.026 mg/m^3 for PM up to 100 μm in diameter versus the *ISS* design specification of 0.05 mg/m^3. Using clean room classifications for comparison, the PM size distribution was found to be similar to three comparable rooms: (1) A class 100,000 clean room for particles <2.5 μm in diameter, (2) a class 400,000 clean room for the 2.5 to <10-μm-size range, and (3) a class 3,000 clean room for the >10-μm-size range. It is interesting to note that STS–32 used only debris filters with a 280-μm nominal filtration rating with no HEPA filtration to achieve this loading. As well, total flow capacity for the Space Shuttle is typically lower than for the *ISS* at 561 m^3/hr (330 ft^3/min) versus the *ISS* total filtered flow of 1,402 m^3/hr (825 ft^3/min). Additonally, the Shuttle's nominal specific ventilation flow per crew member for a crew of seven is nearly 6 times less than the *ISS* specific filtered flow for the normal crew of three. Therefore, it is expected that the suspended PM loading on board the *ISS* may be maintained at a lower level than might be typically experienced on board the Shuttle.

2.2 *International Space Station* Particulate Matter Design Load

The PM design load for the *ISS* BFEs is nearly 2 times higher than the load measured during STS–32. To bound and validate the design, data obtained from Shuttle orbiter postflight debris filter loading assessments and PM generation literature from people during various activities were used to establish a specification design point or load model.[5,6] A test dust for demonstrating BFE performance during qualification testing was specified based on this model. Table 1 compares the test dust particle size distribution to that reported by the STS–32 study and the BFE design specification. As can be seen, the design specification and test dust compare favorably with the findings from the STS–32 study.

Table 1. Comparison of STS–32 and BFE test dust.

Dust	Particle Diameter (μm)	Mass Distribution (%)
STS–32 study	<100	47
	>100	53
BFE test dust	<210	43
	>210	57
BFE design	<100	34
	>100	66

A 2.27×10^4 particles/person-min generation rate was established as part of the load model development from the available data. Compared to the particle size distribution observed during the STS–32 study, the preflight testing and analysis focused more on the larger particle size range generation rate. This is evident because the generation rate for PM <100 µm in diameter is higher than the BFE design model, while the generation rate for the >100-µm-size range is lower.

2.3 Preflight Testing and Analysis

Results from BFE qualification testing indicate a typical clean pressure drop of 70 Pa (0.28 in H_2O) at 119 m^3/hr (70 cfm), and the capacity to load with ≈50 g of the test dust before the allowable pressure drop was exceeded. The loading observed during qualification testing is 56 percent higher than the specified 32 g. Engineering analysis conducted before flight also indicated that even when challenged with very high particulate generation rates on the order of 1.8×10^6 to 5.6×10^6 particles/min, the specified cabin particulate concentration is maintained with nearly 12 percent margin.[7] It is necessary to note that these generation rates are 79 to 247 times higher than the generation rate from a single person as defined by the BFE design load model.

Results from additional preflight engineering analysis that considered the design specification generation rate of 1.4×10^6 particles/min and qualification test mass loading on each filter of ≈50 g indicated a service life of 1-yr or more.[8] As noted previously, this analysis also is considered conservative because the generation rate basis is nearly 62 times that of a single person.

It is evident that all of the preflight engineering analyses and testing demonstrate that the BFEs can outperform their design specification for the defined PM loads. Also, the crew size on board the *ISS* typically is smaller than the loads considered for qualification. Therefore, it is considered likely that the BFE service life may be extended beyond 1-yr if supported by data collected from postflight evaluation.

3. POSTFLIGHT EVALUATION OF *INTERNATIONAL SPACE STATION* FILTER ELEMENT LOADING

Because preflight testing and engineering analysis indicate that the 1-yr BFE service life may be highly conservative, several filter elements have been evaluated postflight to determine their pressure drop over a range of airflow rates. Based on these data, the service life can be reevaluated.

A total of 12 BFEs were returned from the *ISS* for evaluation: 4 from Unity, 6 from Destiny, and 2 from Quest. The accumulated service duration for the returned BFEs are 299 days from Unity, 334 days from Destiny, and 402 days for Quest. The average accumulated service duration is 335 days. The pressure drop for 11 of the 12 BFEs was measured over a range of airflow conditions using the test stand schematic shown in figure 3 and the procedure contained in appendix A. The 12th BFE was selected for microbiological evaluation; therefore, its pressure drop was not evaluated to avoid exposure to the environment on the ground.

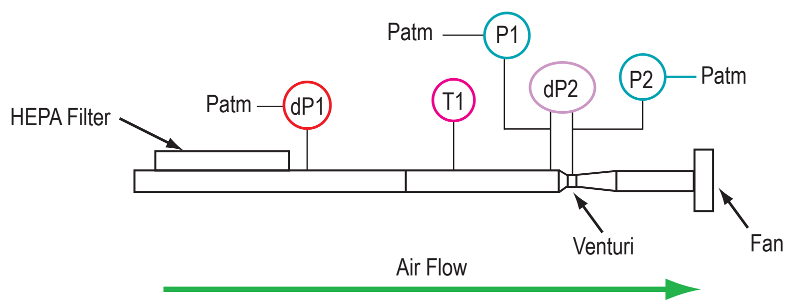

Figure 3. Simplified test stand schematic.

3.1 Test Conduct

The pressure drop evaluation test stand includes a flight-like BFE housing connected to a mocked-up forward section of the ventilation system in Destiny, a Flow-Dyne Engineering, Inc., venturi flowmeter (serial No. 42111) calibrated over the range of zero to 425 m^3/hr (zero to 250 cfm), and a fan to provide motive force. Figure 4 shows the BFE housing and duct mockup. Instrumentation measured ambient temperature and pressure to allow proper air density adjustment, as well as static pressure at precise locations in the test duct and venturi. Sensor data were archived using an automated data acquisition system. Testing was performed in a portable clean room to minimize additional particulate loading during the test.

Figure 4. BFE housing and duct mockup.

Initially, a blank test run was conducted over the entire airflow range with no BFE installed in the test stand. Data from this run determined the pressure drop contribution of the test stand itself, which was subtracted from the readings recorded for each BFE to determine the true filter element pressure drop. Figure 5 shows that the test stand's contribution to pressure drop varies from 2.24 Pa (0.009 in H_2O) to 11.4 Pa (0.046 in H_2O) over the flow range specified for the test.

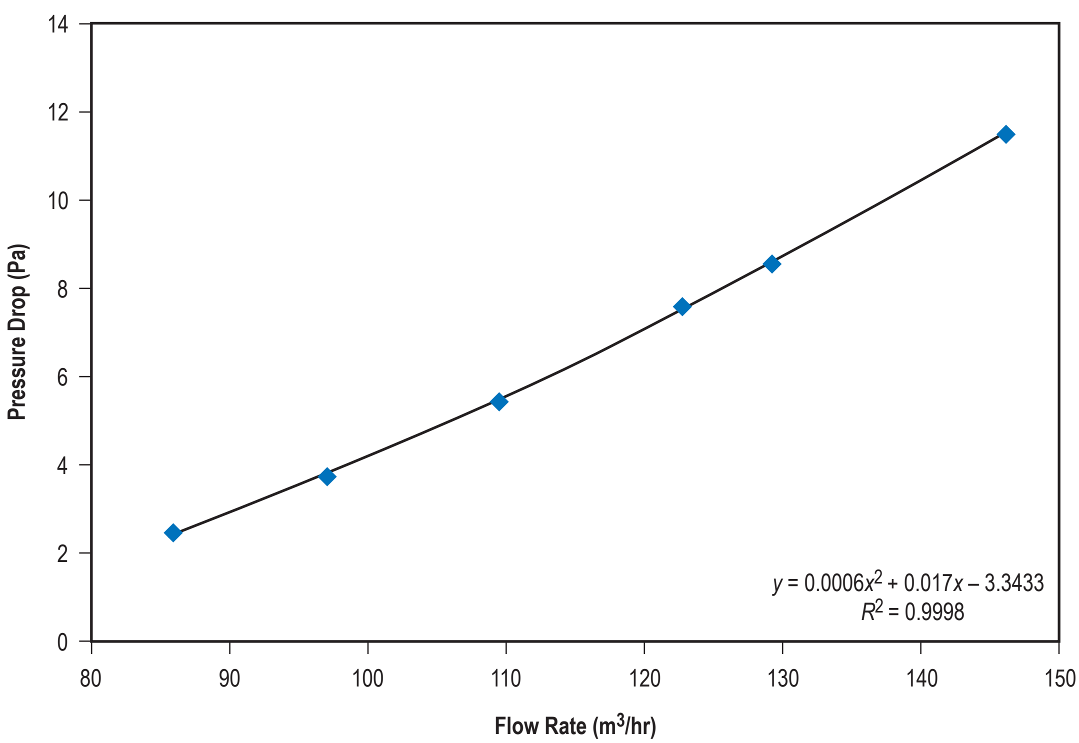

Figure 5. Test stand pressure drop contribution.

In the second testing phase, each BFE was weighed and then installed in the test stand according to the test requirements. The airflow rate was adjusted to 85 ± 8.5 m^3/hr (50 ± 5 cfm). Static pressure just downstream of the BFE was measured and recorded before adjusting the airflow rate to the next setting. Flow rates investigated in addition to the initial setting were 93, 110, 127, and 144 m^3/hr (55, 65, 75, and 85 cfm). The filters were weighed again after testing to confirm that the testing did not have a significant effect on the BFE loading.

Two of the BFEs had significant lint loading on the face. One of the BFEs, serial No. 0011, was subjected to microbiological evaluation and not tested. The second BFE was tested with the lint cake intact and with the lint removed. This allowed for the pressure drop contribution attributed to lint to be evaluated. Additionally, an independent evaluation using dense lint collected from a residential clothes dryer was conducted to understand the effect that heavy lint loading may have on pressure drop.

3.2 Results and Discussion

Table 2 lists the average pressure drop as a function of airflow for the 11 BFEs tested after adjustment to account for the test stand's pressure drop contribution. Appendix B lists the raw data for each BFE and appendix C summarizes the statistical treatment of those data. The reduced data can be described by the power curve relationship shown by equation (1):

$$\Delta P = 0.5373 v^{1.0439} \quad , \qquad (1)$$

where

ΔP = pressure drop (Pa)
v = flow rate (m^3/hr).

This equation is plotted in figure 6. The 95-percent confidence interval, defined as the mean ±1.96 times the standard deviation (σ) is represented by the error bars in figure 6. Figure 6 shows the relationship between the measured pressure drop and the clean and dirty filter pressure drop specifications.

Table 2. Measured BFE pressure drop.

Flow (m^3/hr)	ΔP (Pa)	σ (Pa)	1.96σ (Pa)
85.05	55.8	3.91	7.67
93.51	61.32	5.12	10.03
110.7	72.42	5.85	11.46
127.6	84.92	7.53	14.77
144.6	97	8.39	16.44

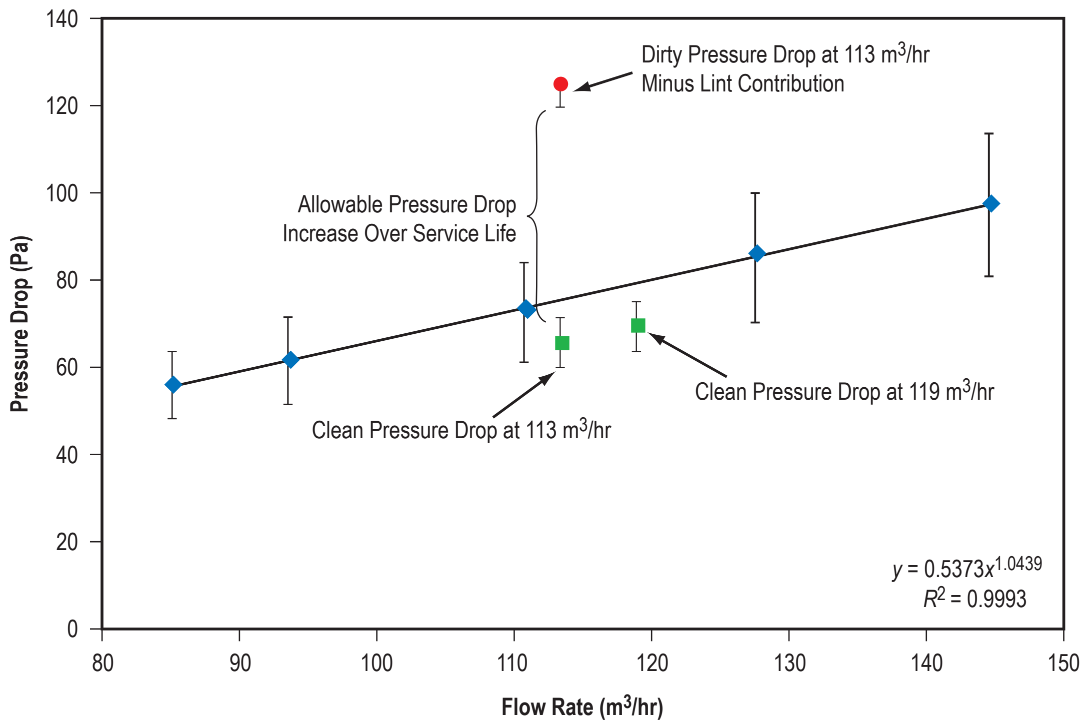

Figure 6. Postflight measured BFE pressure drop versus clean and loaded specifications.

Figure 7 shows the effect that lint buildup on the BFE face has on pressure drop. On average, the pressure drop that can be attributed to lint buildup is approximately 4.98 Pa (0.02 in H_2O). Lint density has a significant effect on BFE pressure drop as shown in figure 8. Evaluation of figures 7 and 8 illustrates that heavy lint buildup negatively affects pressure drop; therefore, it is prudent to employ periodic preventive maintenance to remove lint from the filter face to allow optimum management of BFE resources. In addition, for the purpose of BFE service interval prediction, it is prudent to adjust the specified maximum allowable loaded pressure drop downward by 4.98 Pa to 119.6 Pa (0.48 in H_2O). This adjustment effectively provides operational margin and adds conservatism to the service interval derived from the test data. Figure 6 shows this adjustment and is included in the evaluation of service interval.

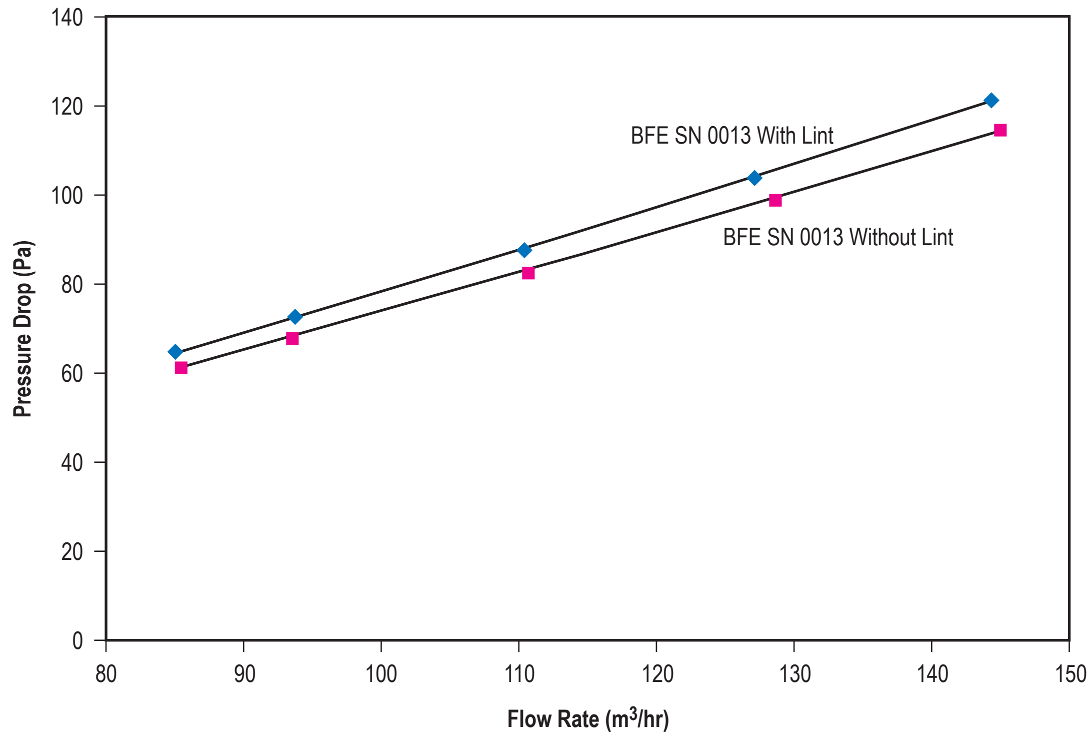

Figure 7. Effect of lint loading on BFE pressure drop.

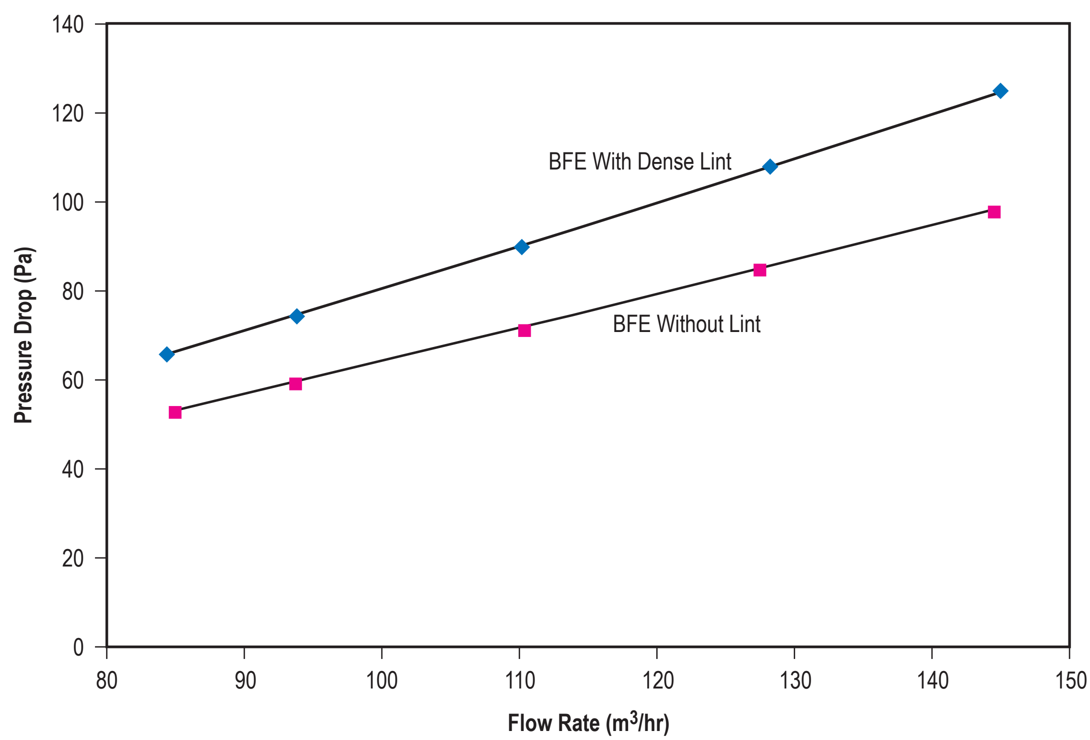

Figure 8. Effect of dense lint loading on BFE pressure drop.

Based on the test data, the daily pressure drop rise is calculated. Several steps comprise the calculation. For the first step, the clean pressure drop at 113 m^3/hr (66.7 cfm) is estimated using the vendor-reported clean pressure drop at 119 m^3/hr (70 cfm) as a reference. These points are illustrated in figure 6. It is assumed that the difference between the measured average pressure drop and clean pressure drop remains constant across the flow range. This places the clean pressure drop for the design specification flow rate of 113 m^3/hr at approximately 65 ± 13.5 Pa (0.26 ± 0.02 in H_2O) for the 95-percent confidence interval. For the second step, the loaded filter pressure drop for the confidence interval upper bound is calculated. Equation (1) is used to calculate the average pressure drop and 11.5 Pa (1.96 σ) is added to the result. The result is approximately 86.4 Pa (0.35 in H_2O). The difference between clean and loaded pressure drop (86.4 Pa – (65 ± 13.5 Pa)) divided by the average 345-day service duration yields a daily pressure drop rise ranging from 0.048 Pa/day (1.9×10^{-4} in H_2O/day) to 0.080 Pa/day (3.2×10^{-4} in H_2O/day) over the confidence interval. Compared to the maximum allowable loaded pressure drop adjusted for lint buildup, the total net allowable pressure drop increase ranges from 48.9 Pa (0.2 in H_2O) to 59.9 Pa (0.24 in H_2O) for the 95-percent confidence interval.

Based on the daily pressure drop rise derived from the test data and the maximum allowable net pressure drop, the predicted service life ranges from 745 days (2.04 yr) to 1,012 days (2.77 yr) for the 95-percent confidence interval. The median between the upper and lower bounds for the confidence interval is 2.4 yr. Adjusting the maximum allowable pressure drop downward provides for a built-in margin ranging from 62.5-d to 105.3-d for the confidence interval. Therefore, with appropriate preventive maintenance, the BFEs should be quite capable of meeting a 2-yr service interval with some margin. Similar analysis for the 98- and 99-percent confidence intervals results in median service life estimates of 2.07 and 1.86 yr, respectively. Since both the upper and lower bounds for the 95-percent confidence interval fall above 2-yr, the predicted service life for the BFEs is 2-yr with a minimum 95 percent confidence. It should be noted that this estimate assumes that the crew will periodically remove lint that accumulates on the BFE prescreen to help manage the rate of pressure drop increase.

3.3 Microbiological Considerations

Besides filter element pressure drop, microbial growth within the filter element during normal use must be considered. While one filter element was subjected to evaluation for the types of microbes present on the filter media surfaces, this evaluation could not address microbial proliferation or breakthrough because the BFEs were transported in bags with the inlet and outlet faces exposed to each other. Therefore, experienced microbiology personnel both within and outside NASA were consulted to obtain a professional position regarding microbial proliferation within the BFEs while in service. The results of this communication are included as appendix D.

In summary, the microbiology experts consulted agreed that microbes on the filter media will die within a few days. Maintaining the cabin relative humidity below 60 percent and at the prevailing cabin temperature of ≈21 °C, no microbial proliferation is expected. Evidence was cited in the paper published by G. Ko et al., that reports low survival rates beyond 48-hr for mycobacteria on HEPA filtration media.[9] Furthermore, as long as the BFE structural integrity is maintained, good containment of microbes should be achieved. This information should be given consideration when conducting BFE preventive maintenance so maintenance procedures avoid damaging the BFEs and that ventilation flow is shut off during BFE replacement to minimize microbial ingestion into the ventilation system.

3.4 Impact to the *International Space Station* Program

By extending the BFE service life to 2-yr, the *ISS* program may realize significant savings in the form of reduced logistics needs and associated costs, less crew time associated with BFE maintenance, and equipment cost savings. Over 15 yr, implementing the 2-yr service life reduces the number of BFEs required for Destiny, Unity, and Quest by ≈152 units. Each BFE is valued at $25,000, yielding equipment savings of $3,800,000. The total logistics launch mass and volume saved is 324 kg and 1.7 m^3. Crew time saved is estimated to be ≈19 hr.[10] At $22,000/kg ($10,000/lb) and $15,000/hr, launch and crew time savings are valued at $7,128,000 and $285,000.[11] The total estimated 15-yr savings is $11,213,000 or $747,533/yr. While assigning monetary value to many of these parameters is difficult, this exercise dramatically illustrates the tangible benefits of extending the BFE service interval. Given these projected savings, the cost of conducting the BFE testing is recovered within 2 wk of implementing the 2-yr service interval.

4. SUMMARY AND CONCLUSION

The design basis and approach to controlling PM in a crewed spacecraft cabin was presented and discussed. In the case of the *ISS*, this discussion established that the design approach is conservative, leading to a conservative filter element design and initial service life estimate. Postflight evaluation of BFE pressure drop after an average 345 days of service on board the *ISS* allowed for the projected service life to be estimated at >2 yr with at least 95 percent confidence. Significant logistics, crew time, and equipment cost savings can be realized by extending the service life to 2 yr.

APPENDIX A—TEST REQUIREMENTS

Prepared by:
K.M. Medley and J.L. Perry
June 17, 2002

Attachment to:
NASA Memorandum FD21(02-084) dated July 11, 2002

TEST REQUIREMENTS

INTERNATIONAL SPACE STATION BACTERIA FILTER ELEMENT PRESSURE DROP EVALUATION

1.0 Background

The International Space Station (ISS) uses High Efficiency Particulate Arrestance (HEPA) filters to remove particulate matter (PM) from the cabin atmosphere. Known as Bacteria Filter Elements (BFE), there are 6 elements deployed in the U.S. Laboratory and 4 elements in Node 1. After approximately 1 year in service, the filter elements are replaced. The first set of BFEs was replaced on January 11, 2002. At the time of replacement, the 6 BFEs in the U.S. Laboratory had been in use for 330 days while those in Node 1 had been in use for 296 days. The life estimate for BFEs is 1 year. To validate this estimate, the BFEs removed from the U.S. Laboratory and Node 1 in December 2001 will be evaluated for pressure drop over a range of air flow conditions.

2.0 Purpose

The current estimate of life expectancy for a BFE is one year. This estimate is based upon engineering calculations that use filter media loading test data and an assumed PM loading in the cabin. By testing the first set of BFEs returned from the ISS, it will be possible to determine if the 1-year life estimate is appropriate or needs adjustment. Testing will be done using a flow bench setup. There is not a specified flow rate for the BFE but it is determined to be approximately 65 cfm. Therefore the testing will involve a range of flow rates that will include that of the filter.

3.0 Test Equipment

The pressure drop of each BFE will be evaluated using the setup shown in Figure 1. The setup includes an adapter to hold the BFE, a duct transition from rectangular to circular cross section, a Flow-Dyne Engineering, Inc. venturi Serial Number 42111 calibrated over the range of 0-250 cfm (see Attachment A-1), and a fan to provide motive force through the test setup. Instrumentation for this setup is described in Section 4.

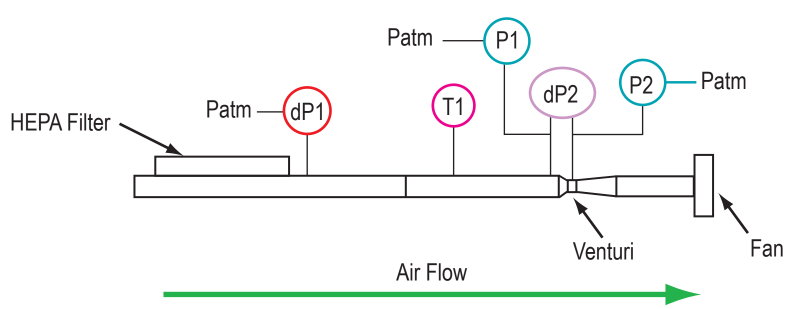

Figure 1. Simplified Test Bench Schematic

4.0 Instrumentation

Appropriate instrumentation will be provided to measure air flow, temperature, and pressure drop through the venturi and pressure drop across the BFE test article. Attachment A-1 provides the calibration data and resulting equation that relate venturi pressure drop to volumetric flow. Table 1 shows the minimum instrumentation requirements, measurement units, and measurement range (sensor measurement descriptions match those on the Venturi and Flow Nozzle Flow Range Curve for Air chart in Attachment A-1).

Table 1. Minimum Test Instrumentation

Sensor Measurement	Name	Units	Range
Pressure drop across filter	dP1	inches H_2O	0–2
Inlet temperature	T1	°F	50–95
Inlet static pressure	P1	inches H_2O	0–5
Pressure drop from inlet to venturi	dP2	inches H_2O	0–5
Venturi throat static pressure	P2	inches H_2O	0–10

5.0 Pre-test Requirements

Before testing, the following will be accomplished:

- Measure and record all flow bench pressures across the entire test flow range with no BFE installed in the test stand.
- Visually inspect each BFE and photograph the inlet face at a minimum.
- Measure and record the weight of each BFE.

6.0 Test Conditions

- Install BFE into the test stand
- Set fan speed to achieve 50 ± 5 cfm flow through the venturi
- Measure pressure drop across the BFE
- Incrementally increase the air flow rates to 55, 65, 75, and 85 cfm and record the pressure drop across the BFE at each flow condition. All flow conditions should be within ± 5 cfm of the target flow.
  (Note: Qualification flow condition for a loaded filter element was 66.7 cfm. Ref. HSSSI Test Engineering Report TER3786 dated April 29, 1996.)
- Measure and record the post-test weight.
- Repeat the sequence for each BFE

7.0 Facility Requirements

The facility will provide all test setup, equipment, and procedures. All necessary sensors will be provided to determine the pressure drop, air flow rate through the venturi, and all temperatures and pressures as shown in Figure 1. A duct transition should be added upstream of the venturi to change the 28 × 4 inch BFE cross section to the smaller, circular cross-section of the venturi. The appendix lists size of tubes necessary and venturi flow range selection chart for air.

Attachment A-1

FLOW DYNAMICS, INC.
15555 N. 79th Place Scottsdale, AZ 85260

Flow Dynamics, Inc. is an ISO 9002 registered company for the calibration, certification and testing of gas and liquid flow measurement devices.

C A L I B R A T I O N   R E P O R T

Customer Name: Flow-Dyne Engineering
Customer PO No: 4211
Meter Type: SUBSONIC FLOW NOZZLE
Fluid Type: AIR

Report No. : 8394-1
Cal Date: 04-04-2000
Serial #: 42111
Model # : V801940-SHC

STP 70 Deg f., 14.7 PSIA

#	Meter Pres: PSIA	Delta P: In H2O @4C	Meter Temp: Deg F	Std. Flow: SCFM (70F)	Downstream: Pres PSIA	Reynolds #: Throat	Cd
1	14.018	0.53649	78.81	57.0596	14.02	45116.78	0.965755
2	14.002	0.69758	82.30	64.9333	13.96	51055.79	0.967658
3	14.016	1.14410	80.54	83.6124	14.00	65926.86	0.971517
4	14.008	1.36160	82.46	91.1229	13.97	71628.93	0.972832
5	14.032	2.01078	78.76	111.360	14.02	88056.62	0.975120
6	14.030	3.39140	82.18	144.290	13.98	113470.7	0.977906
7	14.037	4.12311	81.72	159.314	13.98	125379.9	0.979605
8	14.057	5.90122	81.48	190.742	14.02	150170.2	0.981968
9	14.067	7.12466	81.52	209.730	14.02	165110.5	0.984051
10	14.089	9.89965	82.09	246.615	14.02	193971.1	0.985348

The instrument referenced above was calibrated using standards traceable to the National Institute of Standards and Technology. Evidence of traceability is on file at our laboratory and is available upon request. The volumetric flowrates reported are within an uncertainty of +/- 0.25% of reading.
FDI Calibration Procedure used: FDP-001.
Flow Dynamics, Inc. calibration services comply with MIL-STD-45662A, ANSI Z540-1-1994, ISO GUIDE 25 and ISO 9002:1994.
ANY REPRODUCTION OR REPRESENTATION OF THIS DATA, EXCEPT IN FULL, MUST NOT INCLUDE ANY CLAIM OF COMPLIANCE WITH THE ABOVE MENTIONED STANDARDS.

Calibrated by: A. Walsh
Certified by: [signature]
Date: 4-6-2000

Equipment No: FDI-100
Calibrated: 12/07/99
Recal due: 12/07/00

- CRITICAL FLOW VENTURIS
- VENTURI TUBES
- FLOW NOZZLES
- ORIFICE PLATES AND FLANGES
- METER RUNS
- TEST STANDS AND SYSTEMS

PRIMARY FLOWMETERS
SINCE 1959

FLOW-DYNE *Engineering, Inc.*
MAIL – P.O. Box 161655 • Fort Worth, Texas 76161-1655
PLANT – 4108 Garland Drive • Fort Worth, Texas 76117
TEL. 817-281-6448 FAX: 817-581-0936

- *Consulting*
- *Design & Testing*
- *Development*
- *Manufacturing*
- *Calibration*
- *Software*

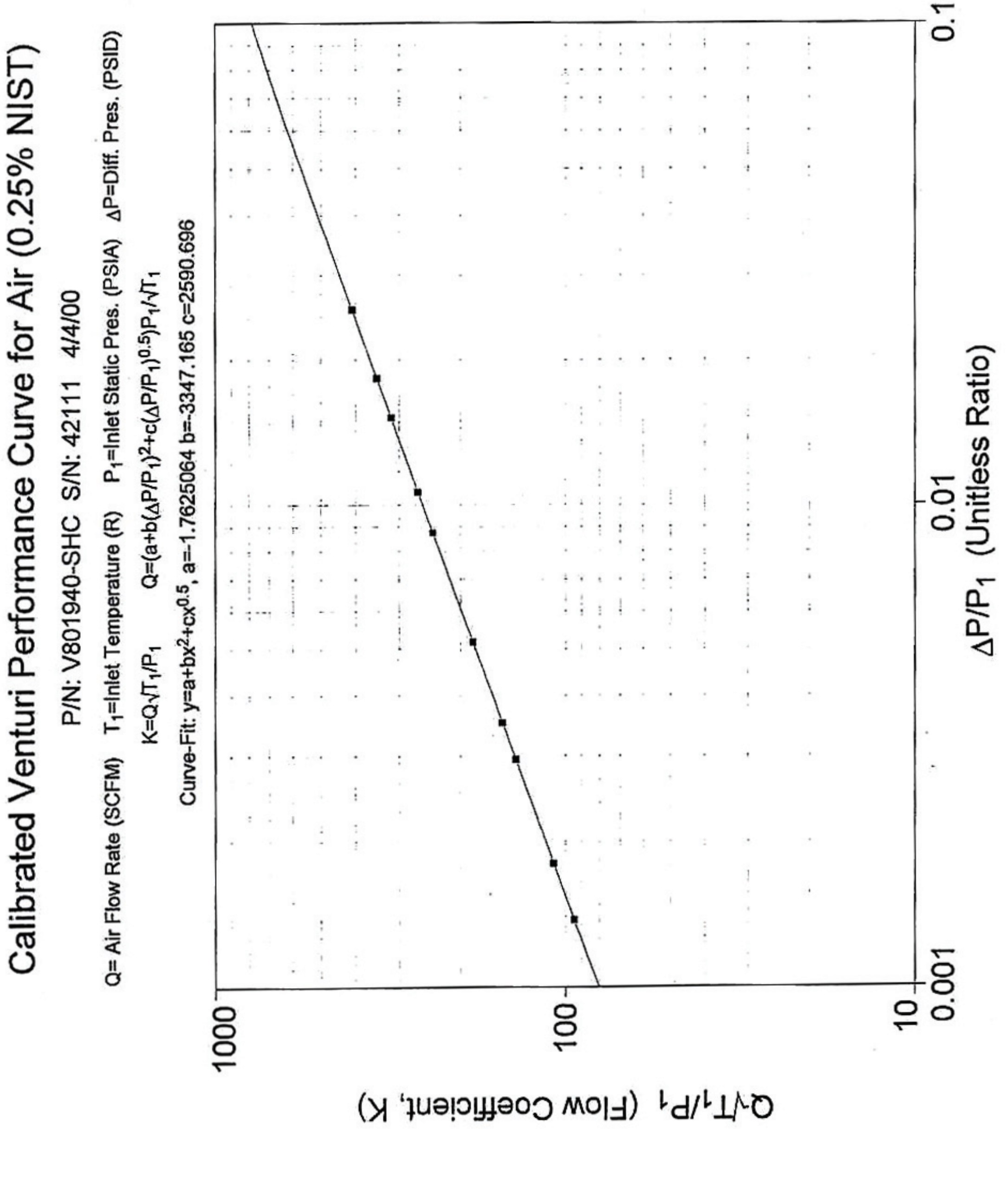

Table 1 Recommended Straight Lengths for ASME Venturi Tubes[A]
(for 0.5% Additional Uncertainty)

Diameter Ratio	Single 90° Short Radius Bend (1)	Two or More 90° Bends in the Same Plane (1)(2)	Two or More 90° Bends in Different Planes (1)(2)(3)	Reducer 3D to D Over a Length of 3.5D	Expander 0.75D to D Over a Length of D	Ball or Gate Valve Fully Open
0.30	0.5[4]	0.5	0.5	0.5[4]	0.5	0.5
0.35	0.5[4]	0.5	0.5	0.5	0.5	0.5
0.40	0.5[4]	0.5	0.5	0.5	0.5	1.5
0.45	0.5	0.5	0.5	0.5	1.0	1.5
0.50	0.5	1.5	8.5	0.5	1.5	1.5
0.55	0.5	1.5	12.5	0.5	1.5	2.5
0.60	1.0	2.5	17.5	0.5	1.5	2.5
0.65	1.5	2.5	23.5	1.5	2.5	2.5
0.70	2.0	2.5	27.5	2.5	3.5	3.5
0.75	3.0	3.5	29.5	3.5	4.5	3.5

Notes:

(1) The radius of curvature of the bend shall be equal to or greater than the pipe diameter.
(2) The insertion of 5D to 10D straight lengths between the two bends is sufficient to make the combined effect the same as the single bends in the left column.
(3) Data have been published which would suggest that after two elbows in the same plane, less error in coefficient would be found by eliminating all straight upstream pipe.
(4) These lengths require no additional uncertainty but the shorter lengths are not proven sufficiently to be published in this Standard.

(A) ASME MFC-3M-1989 : Measurement of Fluid Flow in Pipes using Orifice, Nozzle, and Venturi

APPENDIX B—BACTERIA FILTER ELEMENT MEASURED PRESSURE DROP SUMMARY

Individual BFE measured pressure drops are shown in table B.1.

Table B.1. Individual BFE measured pressure drop (not adjusted for test stand contribution).

Serial No.	Flow (cfm)	Pressure Drop (in H_2O)	σ (in H_2O)
SN 0009 0.29 @ 70	49.66749 55.15298571 65.49086316 75.06551379 85.36286	0.23064258 0.26116581 0.319701737 0.375705759 0.43928752	0.000998168 0.001521941 0.001737686 0.001367962 0.002751732
SN 0010 0.29 @ 70	50.31201364 55.08281364 65.11004 75.22166047 85.30685167	0.251808697 0.280228818 0.341334971 0.404913209 0.471654283	0.002905416 0.003554208 0.001556597 0.002047605 0.002421964
SN 0013 0.30 @ 70	50.21897333 54.96996 65.10671333 75.6876 85.29318889	0.242879933 0.2702456 0.329924533 0.3954586 0.457956278	0.001081398 0.003805858 0.001879994 0.001918716 0.001831226
SN 0013 with lint	49.97539172 55.08996364 64.93653784 74.75597 84.98103488	0.255762531 0.287407045 0.348975676 0.4138737 0.483588698	0.001886937 0.001066939 0.001571149 0.001947776 0.002203531
SN XSR02 0.272 @ 70	49.92616667 55.21032857 65.6298375 75.15048696 85.31970417	0.224767074 0.252858524 0.309068 0.362183478 0.421086667	0.001525667 0.004831357 0.002766109 0.001774412 0.002803674
SN XSR03 0.276 @ 70	49.76454615 55.08739 65.65301563 75.18217 85.51791429	0.218634077 0.2450725 0.300734906 0.3520277 0.409348429	0.001224258 0.00116968 0.001958468 0.00144719 0.002525875
SN XSR04 0.262 @ 70	50.42073684 55.09581111 64.9545875 75.00913636 84.70154	0.210197895 0.232905852 0.281646875 0.333504545 0.3855376	0.002766401 0.002745804 0.001330364 0.002367824 0.002382616
SN XSR05 0.274 @ 70	50.32433 54.82808095 64.960175 75.023225 84.76700244	0.2162707 0.239041619 0.29091225 0.343244667 0.396399098	0.001406277 0.00252098 0.001658594 0.001948081 0.001857208

Table B.1. Individual BFE measured pressure drop (not adjusted for test stand contribution) (Continued).

Serial No.	Flow (cfm)	Pressure Drop (in H_2O)	σ (in H_2O)
SN 0093 0.27 @ 70	49.88786 55.30347778 65.29568636 74.96741111 84.92703636	0.22655292 0.256385389 0.312697682 0.368349111 0.429076	0.002610274 0.001285213 0.00192761 0.002284278 0.002102382
SN 0094 0.28 @ 70	49.82399444 54.94632 64.77013333 75.03704286 84.82141579	0.266739833 0.29984296 0.364575625 0.436640571 0.506914947	0.002479775 0.002012469 0.001535647 0.003346511 0.003204434
SN 0071 0.27 @ 70	49.967288 55.04107778 65.334552 75.26422222 85.115405	0.22367584 0.250921667 0.30784392 0.365468667 0.424593075	0.00110469 0.001429853 0.002161967 0.001685405 0.002285898
SN V0201 0.27 @ 70	50.4133 54.790975 64.85748868 74.79486078 84.69138182	0.218746867 0.240511393 0.292340698 0.345243353 0.400327636	0.00119562 0.001267445 0.001109496 0.003171808 0.00155089
Test Stand	50.4692 56.99681667 64.28767857 72.13536667 75.95391538 85.84702571	0.009644607 0.014783678 0.021536371 0.03013435 0.034055438 0.045857006	3.38863×10^{-5} 0.00048183 0.000572455 0.001036684 0.000452389 0.00077053
Lab Test Unit Clean	50.21897333 54.96996 65.10671333 75.6876 85.29318889	0.242879933 0.2702456 0.329924533 0.3954586 0.457956278	0.001081398 0.003805858 0.001879994 0.001918716 0.001831226
Lab Test Unit Dense Lint	49.97539172 55.08996364 64.93653784 74.75597 84.98103488	0.255762531 0.287407045 0.348975676 0.4138737 0.483588698	0.001886937 0.001066939 0.001571149 0.001947776 0.002203531

APPENDIX C—TEST DATA STATISTICAL SUMMARY

Composite BFE pressure drop statistical evaluation is shown in table C.1, BFE clean pressure drop summary in table C.2, BFE end-of-life requirement in table C.3, and composite pressure drop summary and statistical sampling for all tested BFEs in table C.4.

Table C.1. Composite BFE pressure drop statistical evaluation.

	Air Flow	Measured Pressure*	Test Stand	BFE Pressure**	Standard Deviation	1.96s
English Units	(cfm)	(in H_2O)	(in H_2O)	(in H_2O)	(in H_2O)	(in H_2O)
	50.06391	0.23316	0.009151	0.224009	0.015705	0.030783
	55.03767	0.259488	0.013308	0.24618	0.02054	0.040259
	65.17229	0.313588	0.022849	0.290739	0.023477	0.046015
	75.08501	0.374497	0.033573	0.340924	0.030245	0.059281
	85.10133	0.435252	0.045806	0.389446	0.033674	0.066001
SI Units	(m^3/hr)	(Pa)	(Pa)	(Pa)	(Pa)	(Pa)
	85.05952	58.07497	2.279314	55.79566	3.911883	7.667291
	93.51004	64.6328	3.314732	61.31807	5.11617	10.02769
	110.729	78.1079	5.691187	72.41671	5.847639	11.46137
	127.5708	93.27905	8.362301	84.91675	7.533457	14.76557
	144.5888	108.4117	11.40927	97.00244	8.387457	16.43942

* Includes test stand contribution
** Minus test stand contribution

Table C.2. BFE clean pressure drop summary.

	Air Flow		BFE Pressure		Standard Deviation		1.96s	
	(cfm)	(m^3/hr)	(in H_2O)	(Pa)	(in H_2O)	(Pa)	(in H_2O)	(Pa)
Individual Filter Summary	70		0.29					
	70		0.29					
	70		0.3					
	70		0.272					
	70		0.276					
	70		0.262					
	70		0.274					
	70		0.27					
	70		0.28					
	70		0.27					
	70		0.27					
Average Clean Pressure Drop	70	118.9313	0.277636	69.15316	0.011307	2.816396	0.022162	5.520137

Table C.3. BFE end-of-life requirement.

Air Flow		BFE Pressure	
(cfm)	(m^3/hr)	(in H_2O)	(Pa)
66.7	113.3246	0.5	124.5391

Table C.4. Composite pressure drop summary and statistical sampling for all tested BFEs.

Raw Composite Data Sampling for All Tested Filter Elements									
Flow Rate 1 (cfm)	Measured Pressure 1 (in H_2O)	Flow Rate 2 (cfm)	Measured Pressure 2 (in H_2O)	Flow Rate 3 (cfm)	Measured Pressure 3 (in H_2O)	Flow Rate 4 (cfm)	Measured Pressure 4 (in H_2O)	Flow Rate 5 (cfm)	Measured Pressure 5 (in H_2O)
49.7988	0.230552	55.9701	0.265426	65.1094	0.317293	74.7174	0.374067	84.8467	0.437738
49.7105	0.230786	54.9494	0.259745	65.2684	0.31702	75.0393	0.375678	84.7197	0.432655
49.7949	0.230076	55.0853	0.260036	64.7883	0.318047	74.6678	0.373486	85.2467	0.43968
49.6927	0.229818	55.4161	0.262496	64.997	0.316169	75.2791	0.376633	85.0508	0.437618
49.6648	0.230368	55.1934	0.260393	65.1388	0.318163	75.4972	0.375167	85.4379	0.437764
49.607	0.230231	55.1782	0.261025	65.5053	0.319515	74.8696	0.375951	85.2675	0.440148
49.7651	0.231252	55.197	0.261863	65.5102	0.319517	75.1109	0.374894	85.2497	0.438452
49.9166	0.232869	55.0411	0.259223	65.4038	0.321217	75.103	0.375977	85.5665	0.440368
49.6391	0.23036	55.1475	0.26143	65.9453	0.322485	75.2867	0.376516	84.6776	0.434322
49.6294	0.229372	55.1162	0.262464	65.3992	0.31902	74.9993	0.374079	85.9894	0.444874
49.7155	0.229871	54.9929	0.258651	65.7904	0.319954	74.978	0.37608	85.492	0.440246
49.9948	0.230838	55.1278	0.261565	65.4885	0.320276	75.4156	0.376123	85.154	0.438662
49.4587	0.229284	55.2949	0.262033	65.8668	0.321894	75.295	0.377275	85.6062	0.44124
49.8791	0.23111	55.0639	0.260808	65.7161	0.32153	75.057	0.3763	85.2874	0.437162
49.7431	0.231218	55.2507	0.262163	65.7024	0.320178	75.021	0.376132	85.3983	0.440393
49.6598	0.229279	54.961	0.259724	65.7313	0.319713	74.9236	0.376894	85.548	0.441322
49.4987	0.229732	55.0628	0.261154	65.5816	0.320387	74.9368	0.37461	84.9331	0.435357
49.4252	0.229793	55.2624	0.260883	65.7187	0.320385	74.9598	0.375692	85.3588	0.435763
49.4749	0.229362	55.0245	0.262628	65.6649	0.32157	74.871	0.374765	85.624	0.441069
49.6052	0.229256	54.7354	0.259244	64.447	0.338617	75.1379	0.377169	85.384	0.440968
49.6862	0.231354	55.1421	0.261528	64.7792	0.338971	75.0947	0.376161	85.3819	0.442008
49.6604	0.231044	55.014	0.280132	64.4977	0.337462	74.8781	0.375723	85.4506	0.440236
49.5069	0.23044	55.3807	0.283113	64.8222	0.34052	74.8375	0.374683	85.9542	0.440889
49.8441	0.231878	55.8456	0.284803	64.852	0.339606	75.4757	0.37862	85.6967	0.440948
49.78	0.23025	56.063	0.285881	64.8945	0.33919	74.9673	0.371744	85.7498	0.442306
49.3537	0.229246	55.6349	0.282287	65.3181	0.342475	75.0782	0.376116	85.1169	0.469938
49.7674	0.231545	55.7156	0.2862	65.2516	0.341646	75.1662	0.375412	85.1933	0.473197
49.4829	0.22945	55.6545	0.282977	65.317	0.341037	75.0168	0.375605	85.4623	0.471134
49.6501	0.230871	55.6326	0.282368	64.9886	0.339595	75.2194	0.377915	86.0844	0.476071
49.635	0.230256	55.548	0.283551	65.2621	0.342032	74.9288	0.405627	85.6906	0.473698
49.4406	0.230126	55.7341	0.283952	64.988	0.342134	75.3669	0.404741	85.6272	0.474059
49.5736	0.229667	55.7732	0.28378	65.1839	0.344133	75.5928	0.405727	86.149	0.477307
49.7154	0.232092	55.7956	0.284967	64.9663	0.340605	75.4152	0.406084	85.592	0.475693
50.0898	0.233427	55.8255	0.284592	65.1731	0.342258	75.1904	0.404689	85.9359	0.475319
49.4095	0.230001	55.5955	0.281533	64.9579	0.340357	75.3275	0.407276	85.4938	0.469975
49.869	0.231661	55.7554	0.284525	65.1604	0.341927	75.6553	0.406855	85.9203	0.474719
49.5033	0.23064	55.6153	0.283749	65.4206	0.342178	75.8125	0.408611	85.6943	0.475466
49.4697	0.230185	55.6262	0.28198	65.109	0.341544	75.2158	0.4093	85.5684	0.471109
49.7671	0.231941	55.7748	0.284776	64.9441	0.340668	75.3972	0.406365	85.902	0.477272
49.9382	0.232455	55.6211	0.284221	65.2181	0.341341	75.467	0.407178	85.645	0.474607
49.5184	0.230351	55.5787	0.282934	65.3318	0.343662	75.3641	0.406509	85.5952	0.470933
49.5869	0.230842	55.4828	0.283774	65.2441	0.341967	75.5344	0.40739	85.0946	0.471668

Table C.4. Composite pressure drop summary and statistical sampling for all tested BFEs (Continued).

Raw Composite Data Sampling for All Tested Filter Elements									
Flow Rate 1 (cfm)	Measured Pressure 1 (in H_2O)	Flow Rate 2 (cfm)	Measured Pressure 2 (in H_2O)	Flow Rate 3 (cfm)	Measured Pressure 3 (in H_2O)	Flow Rate 4 (cfm)	Measured Pressure 4 (in H_2O)	Flow Rate 5 (cfm)	Measured Pressure 5 (in H_2O)
49.8792	0.231951	54.8528	0.280042	65.2906	0.341273	75.0736	0.401953	85.6201	0.476452
49.4022	0.229718	54.8808	0.278586	65.3374	0.342726	75.7774	0.408764	85.4902	0.471967
49.6902	0.230871	54.8185	0.277346	65.0514	0.339777	75.5406	0.406417	85.193	0.470264
49.6102	0.230658	54.4616	0.276506	65.4	0.342758	75.1979	0.403885	85.6954	0.4712
49.7761	0.231452	54.3052	0.275857	64.9264	0.34069	75.0305	0.404058	85.4006	0.47316
49.6349	0.230564	54.4168	0.275478	65.1485	0.343068	75.0478	0.40559	85.0311	0.469919
49.5059	0.22976	54.2908	0.275222	65.2344	0.34257	75.0102	0.4022	85.052	0.471485
49.9537	0.232006	54.3047	0.275782	65.0549	0.340109	74.9332	0.400725	85.0037	0.47172
50.2693	0.252492	54.6309	0.277034	65.2918	0.342003	75.3873	0.406429	84.8032	0.468082
49.8554	0.249028	54.7257	0.277977	65.1633	0.340966	74.759	0.403081	85.2099	0.471044
49.6444	0.247569	54.6793	0.278937	65.3963	0.342803	75.0986	0.404827	85.2936	0.47224
49.3507	0.244856	54.6676	0.27728	65.4291	0.344056	75.023	0.404547	85.5204	0.47302
49.4511	0.248081	54.8598	0.278428	65.0086	0.329501	75.4305	0.40548	85.1154	0.47141
49.2672	0.245183	54.466	0.277032	65.0619	0.331248	75.0285	0.401079	84.9749	0.46547
49.2632	0.245953	54.4466	0.27667	65.0103	0.329137	74.9326	0.404092	84.8784	0.469771
49.2449	0.245863	54.5018	0.277745	64.5113	0.326409	75.0238	0.405103	84.9872	0.471334
49.3199	0.245175	54.4628	0.277934	65.2758	0.330594	75.1026	0.402762	84.84	0.468095
49.3872	0.24504	54.7233	0.278347	65.2796	0.330512	74.8792	0.404834	85.1731	0.468424
49.2898	0.244608	54.875	0.277918	64.6804	0.325348	75.1765	0.404511	84.6626	0.468941
49.6049	0.246728	54.3573	0.274793	65.2713	0.331235	75.0929	0.404859	85.4035	0.473208
50.3262	0.252076	54.2509	0.275656	65.2883	0.331605	74.935	0.400538	85.1893	0.470218
50.1135	0.250577	54.3988	0.276734	65.1291	0.330578	74.9334	0.402753	85.4062	0.471058
50.5716	0.253125	54.5997	0.276669	64.9663	0.329988	74.852	0.401921	85.054	0.471213
50.2878	0.25241	55.0089	0.270662	65.2018	0.33048	75.0958	0.404143	85.3714	0.472357
50.3361	0.251263	55.642	0.274818	65.2497	0.332444	75.4172	0.404533	85.0505	0.470988
50.6611	0.254028	55.7392	0.272837	65.4174	0.33067	75.4348	0.405815	85.0343	0.471414
50.5691	0.253748	55.5193	0.272668	65.2489	0.329119	75.202	0.405982	85.4139	0.471972
50.6106	0.252997	55.3012	0.273184	64.7509	0.303144	75.4455	0.404221	85.0937	0.471388
50.5271	0.253632	55.6686	0.273768	65.2692	0.306981	75.1225	0.404999	84.9242	0.470119
50.3963	0.252502	55.5551	0.273378	65.2362	0.30525	75.2796	0.404815	85.1839	0.470842
50.5384	0.253067	55.3252	0.27168	65.8768	0.310478	74.907	0.390791	85.1951	0.471933
50.628	0.254399	55.666	0.272925	66.3134	0.312399	75.4132	0.39484	85.416	0.471358
50.4056	0.25261	55.593	0.274449	65.8653	0.311311	75.4809	0.394184	85.0688	0.469925
50.4119	0.251623	55.0689	0.271325	66.1747	0.312933	76.1172	0.397457	85.2333	0.469498
50.8936	0.255481	54.7679	0.268377	66.1818	0.310745	75.9341	0.396123	85.1983	0.469994
50.4716	0.251411	54.802	0.269678	66.1181	0.311357	75.5824	0.39521	84.851	0.470325
50.5992	0.253364	53.8437	0.264685	65.6777	0.30949	75.6515	0.394461	84.7709	0.46556
50.5382	0.252965	53.6946	0.264622	65.7241	0.309903	76.1705	0.398231	85.09	0.471337
50.416	0.252551	53.7892	0.262947	65.6672	0.30987	76.0483	0.398442	85.5657	0.472858
50.535	0.252273	53.8083	0.26396	65.6698	0.310579	76.0518	0.396575	85.3423	0.471306
50.7156	0.254547	54.5571	0.268834	65.1728	0.30718	75.7785	0.395234	85.5326	0.472698
50.2002	0.250801	54.3187	0.266785	65.3739	0.307564	75.5905	0.39535	85.4385	0.471022
50.5297	0.253404	55.7303	0.27333	65.0055	0.305904	75.7733	0.396483	84.8737	0.470503
50.8333	0.25422	55.3149	0.254076	64.7222	0.295823	75.2862	0.393811	85.0886	0.45858
50.2264	0.247628	56.226	0.256991	65.2523	0.298561	75.5286	0.394687	84.8445	0.455247
50.2185	0.253523	56.1841	0.257891	65.1666	0.297467	75.2567	0.36334	85.5058	0.458833
50.4698	0.253328	56.3494	0.258278	65.8956	0.301961	74.8315	0.362915	85.097	0.455203
50.6427	0.253506	56.1526	0.259363	65.4615	0.299619	75.2663	0.362866	85.1839	0.456806
50.5878	0.254693	55.9762	0.257575	65.6132	0.300356	75.1786	0.360907	85.1936	0.458379
50.3475	0.252169	56.5024	0.260235	65.944	0.302976	75.2565	0.361887	85.3958	0.459057
50.6819	0.254001	55.4786	0.254822	65.767	0.300707	75.4919	0.363559	85.2087	0.457344
50.5731	0.25341	54.5282	0.248077	65.4835	0.299408	75.2569	0.36165	85.3983	0.461242

Table C.4. Composite pressure drop summary and statistical sampling for all tested BFEs (Continued).

Raw Composite Data Sampling for All Tested Filter Elements									
Flow Rate 1 (cfm)	Measured Pressure 1 (in H_2O)	Flow Rate 2 (cfm)	Measured Pressure 2 (in H_2O)	Flow Rate 3 (cfm)	Measured Pressure 3 (in H_2O)	Flow Rate 4 (cfm)	Measured Pressure 4 (in H_2O)	Flow Rate 5 (cfm)	Measured Pressure 5 (in H_2O)
50.1175	0.250198	54.209	0.246387	65.7586	0.300784	74.8407	0.359454	85.1808	0.458233
50.5863	0.254106	54.3231	0.248652	65.9676	0.302968	74.8202	0.359458	85.7054	0.460607
50.4687	0.25352	54.1213	0.247839	65.9366	0.302744	75.3481	0.365508	85.6012	0.459644
50.5362	0.25362	54.1866	0.247041	65.6678	0.30029	74.9339	0.359966	85.25	0.457322
50.4658	0.25489	54.0904	0.246834	66.0667	0.302885	74.8719	0.360897	84.7247	0.455276
50.6004	0.253451	54.0971	0.246618	65.93	0.302451	75.0005	0.360829	85.1911	0.455874
50.458	0.253295	54.2316	0.248294	65.9711	0.301306	75.1807	0.361983	85.7247	0.460157
50.497	0.252095	54.8755	0.251529	65.9952	0.301623	75.0087	0.36362	85.4225	0.457387
50.7838	0.255613	55.2803	0.252026	65.4636	0.299279	74.9965	0.360174	85.5608	0.458022
50.5921	0.252638	55.834	0.256194	66.041	0.302693	75.625	0.365311	85.3357	0.423062
50.3723	0.250752	55.5185	0.254239	65.9697	0.303164	75.1602	0.360673	85.7218	0.424689
50.3989	0.254089	55.9371	0.257068	65.6177	0.298901	75.2685	0.363474	86.3342	0.423957
50.7446	0.254078	55.7678	0.247896	65.7178	0.299993	75.2917	0.361909	85.2614	0.419399
50.3083	0.252904	55.0357	0.245355	66.0365	0.30165	75.1616	0.363642	85.6961	0.423809
50.6086	0.254415	55.1504	0.245429	65.6383	0.302261	74.9524	0.361526	85.2316	0.422429
50.3329	0.250555	55.1514	0.245407	65.9035	0.302161	75.4622	0.364672	85.8558	0.424164
50.5107	0.253081	54.9942	0.245318	65.6966	0.302508	74.8479	0.350128	85.7955	0.424818
50.5465	0.253719	54.6066	0.243945	65.8065	0.30208	75.0066	0.351155	85.9616	0.423776
50.4096	0.252161	55.045	0.244583	65.8434	0.302212	75.484	0.352942	85.2953	0.418961
50.3221	0.252111	55.0158	0.2442	65.3659	0.30065	75.4919	0.353849	85.3142	0.421421
50.6061	0.25419	54.6438	0.243804	65.3045	0.298923	74.651	0.35084	85.3221	0.422064
50.5151	0.251985	55.4632	0.244788	64.9363	0.297247	75.2014	0.351127	85.3653	0.421101
49.9583	0.240291	54.1303	0.229493	64.9557	0.297866	74.9619	0.350899	85.351	0.422236
50.0609	0.241845	54.4213	0.230263	64.9042	0.281774	75.1324	0.351705	84.9767	0.421105
50.028	0.242573	54.1997	0.229287	64.6782	0.280408	75.6361	0.354222	85.565	0.423178
50.2129	0.242554	54.2856	0.228972	65.3361	0.284022	75.4085	0.35341	84.9573	0.419951
50.2066	0.242029	54.572	0.229463	64.8413	0.280534	74.7318	0.329966	84.9457	0.415878
50.1231	0.243003	54.0006	0.228054	64.9673	0.28234	73.9159	0.328926	84.5929	0.416059
50.2763	0.243499	54.5137	0.229975	64.8765	0.280738	74.7237	0.331605	84.7714	0.420439
50.2479	0.243344	54.982	0.231235	64.7626	0.282815	75.4468	0.334836	84.9517	0.417072
50.4148	0.242876	55.757	0.234563	65.2464	0.283187	75.1983	0.334283	85.2078	0.418923
50.4362	0.244022	55.7199	0.236773	64.4837	0.280672	74.8979	0.334047	84.9514	0.421648
50.3834	0.244424	55.9397	0.236006	64.8664	0.281368	75.5596	0.336234	84.9114	0.415941
50.0679	0.242267	55.7353	0.236961	64.9831	0.280474	74.9752	0.333071	85.0741	0.405001
50.4103	0.244537	55.9439	0.235241	64.8504	0.279945	75.2417	0.335373	85.2867	0.409065
50.2641	0.24331	55.5981	0.235706	65.0208	0.282137	75.0087	0.334944	85.7503	0.411173
50.1939	0.242625	55.8891	0.236906	65.1401	0.284148	75.4009	0.335265	85.5375	0.409382
50.735	0.229271	55.3957	0.233669	65.0359	0.280625	74.7748	0.342645	85.0252	0.405848
50.5094	0.227069	55.4026	0.235182	65.2804	0.281163	74.5256	0.340086	85.574	0.409369
49.8318	0.224732	55.5763	0.235915	64.8266	0.289575	75.0856	0.344819	85.4022	0.407329
49.8799	0.22424	55.28	0.235221	64.1911	0.287771	75.0592	0.343485	85.8657	0.412358
49.9992	0.225595	54.8961	0.23054	64.8822	0.290254	75.0404	0.339726	85.6783	0.411152
49.841	0.223653	54.8255	0.232501	65.1732	0.292821	74.9114	0.343791	86.1746	0.41287
49.8246	0.224102	55.2027	0.231877	64.7817	0.289769	75.3623	0.342985	85.4378	0.40811
49.6735	0.223028	55.1267	0.232401	65.3672	0.292025	75.3006	0.345131	85.4879	0.409435
49.9853	0.223691	54.8046	0.232003	65.0514	0.291298	75.0046	0.344024	85.7473	0.412847
49.7125	0.224058	55.0399	0.23311	64.7956	0.290208	75.0904	0.34523	85.2092	0.406939
50.1366	0.224938	55.0897	0.233606	65.069	0.292517	74.8397	0.341522	85.1653	0.38938
50.1675	0.225249	55.2589	0.233535	64.7441	0.2899	75.2841	0.345492	84.4268	0.38422
49.9068	0.2241	54.5495	0.238267	65.1678	0.291123	75.0225	0.36799	84.7016	0.384658
49.781	0.224372	54.5065	0.237101	65.4722	0.293686	75.4899	0.371675	84.9493	0.386034
49.9813	0.226585	54.2539	0.235834	65.4844	0.315044	74.5861	0.365689	84.5212	0.384078

Table C.4. Composite pressure drop summary and statistical sampling for all tested BFEs (Continued).

Raw Composite Data Sampling for All Tested Filter Elements									
Flow Rate 1 (cfm)	Measured Pressure 1 (in H_2O)	Flow Rate 2 (cfm)	Measured Pressure 2 (in H_2O)	Flow Rate 3 (cfm)	Measured Pressure 3 (in H_2O)	Flow Rate 4 (cfm)	Measured Pressure 4 (in H_2O)	Flow Rate 5 (cfm)	Measured Pressure 5 (in H_2O)
49.8414	0.222823	54.4153	0.235875	65.3109	0.312885	74.571	0.367301	85.0004	0.388565
49.6544	0.223417	54.3823	0.23693	65.8232	0.314423	74.7689	0.367698	84.9224	0.386675
49.9235	0.223453	54.6079	0.237297	65.8798	0.315054	75.0092	0.366958	84.3781	0.381943
49.7311	0.224356	54.5305	0.238704	65.6225	0.315189	74.9136	0.369133	84.7634	0.386819
49.8852	0.225547	54.5432	0.236849	65.814	0.314061	74.8885	0.366399	84.1869	0.383004
50.1216	0.225399	54.6756	0.237741	65.8261	0.314993	75.457	0.372299	84.8588	0.3987
49.7781	0.223667	54.5777	0.237462	65.4169	0.313199	74.7491	0.434722	84.2904	0.394162
49.6629	0.225301	54.6411	0.238493	65.6805	0.313245	74.5846	0.432874	84.404	0.397054
49.6521	0.223438	54.232	0.236562	65.2789	0.313958	74.4423	0.434539	84.2926	0.395809
49.585	0.22325	54.5216	0.237158	65.3819	0.312732	74.7213	0.434815	84.219	0.393741
49.8491	0.225693	55.0808	0.240263	65.2132	0.311997	74.2236	0.431082	84.5889	0.39704
50.3567	0.227684	55.267	0.240959	65.0132	0.313136	74.3993	0.430578	84.6403	0.396082
50.2617	0.221259	55.4683	0.242388	64.957	0.310578	74.4351	0.431497	84.8696	0.395338
49.8599	0.219079	55.5767	0.242871	65.0223	0.311922	74.5296	0.434891	84.2949	0.395984
49.8763	0.220422	55.2362	0.242049	64.9076	0.310826	75.4623	0.438145	84.4352	0.394065
49.6945	0.218228	55.3299	0.241003	65.0626	0.311162	75.3543	0.436996	84.5191	0.396521
49.4445	0.217923	55.5757	0.243123	65.1968	0.312483	75.0864	0.437286	84.6997	0.395301
49.9677	0.219377	55.418	0.242945	65.0786	0.311502	75.5968	0.440562	84.3182	0.394872
49.3318	0.216761	55.7154	0.25838	64.4173	0.307015	75.5035	0.441354	84.9679	0.397939
49.9503	0.218814	55.4405	0.25777	65.0787	0.312979	75.2568	0.437317	85.001	0.395758
49.8803	0.218817	55.3448	0.256577	65.0387	0.310966	75.1131	0.437593	84.9358	0.395714
49.5591	0.217501	55.6106	0.25788	64.9406	0.365936	75.4612	0.440256	84.904	0.397335
49.7237	0.218111	55.2643	0.256026	64.8073	0.365888	75.0221	0.436592	84.4291	0.394695
49.5428	0.217486	55.2903	0.256115	65.1272	0.366079	75.337	0.438072	84.233	0.394383
49.8465	0.218465	55.296	0.254926	65.0986	0.366506	75.6526	0.43958	84.7241	0.394358
50.7793	0.212827	54.9648	0.255536	64.5387	0.364197	75.7438	0.442368	84.3853	0.394354
50.9864	0.212801	55.1417	0.25527	64.8724	0.362929	75.1031	0.438333	84.9037	0.395899
50.9935	0.211717	55.0451	0.255201	64.4483	0.36232	75.1552	0.365836	85.0594	0.399555
50.9342	0.213135	55.4139	0.257124	64.6047	0.363503	75.594	0.366581	84.4732	0.394746
51.0157	0.213515	55.1959	0.255566	64.9602	0.367037	75.6257	0.368054	84.9345	0.395539
50.8616	0.211567	55.144	0.255668	64.1516	0.362084	74.7196	0.361791	84.1903	0.393258
50.5921	0.212231	55.241	0.25763	64.9258	0.364998	75.2604	0.364981	85.0505	0.3967
50.9876	0.213689	55.4787	0.257694	64.4629	0.364186	75.0566	0.364982	85.0901	0.396869
50.8106	0.212654	55.4238	0.25636	65.084	0.366895	75.3186	0.365484	84.7463	0.396576
50.805	0.212116	55.534	0.257608	64.6986	0.363761	75.4384	0.366257	85.0005	0.396106
50.412	0.209826	54.9178	0.253606	64.6805	0.36416	75.2095	0.365252	85.0559	0.399694
49.7548	0.207585	55.0148	0.29934	64.7232	0.364237	74.9527	0.345298	84.7343	0.395896
50.0877	0.207239	54.6375	0.298426	64.8333	0.364713	75.4747	0.34836	84.8986	0.397416
50.0362	0.208158	54.447	0.297657	64.5839	0.361655	75.4146	0.349879	85.6359	0.399647
49.8924	0.20762	54.6191	0.297181	64.7977	0.363777	75.6186	0.349	85.0486	0.398653
49.6309	0.206716	54.7875	0.29899	64.6722	0.36519	75.4963	0.348343	85.1485	0.39665
49.8427	0.207217	54.9417	0.299629	64.7361	0.365949	75.4008	0.350403	84.986	0.395114
49.72	0.207027	54.8012	0.298791	64.7062	0.365089	75.1988	0.347444	85.6553	0.401104
49.8513	0.20612	54.821	0.299127	64.7634	0.362805	75.0854	0.348444	85.1729	0.398864
50.473	0.217528	54.9576	0.298756	65.2658	0.365921	75.4788	0.348508	84.9399	0.399131
50.1135	0.215794	54.7927	0.29806	65.6414	0.308842	75.5505	0.348189	84.7118	0.395741
50.3644	0.21715	54.8047	0.300201	65.8512	0.311051	75.3096	0.348846	84.7317	0.427574
50.2923	0.215764	54.6796	0.299106	65.4242	0.309664	75.0172	0.346047	85.13	0.432785
50.5416	0.218514	54.6132	0.296821	65.5974	0.309539	75.088	0.346979	85.1898	0.429834
50.1733	0.215217	55.0871	0.299176	65.583	0.309669	75.1153	0.347771	84.6032	0.427546
50.147	0.214529	54.8124	0.300022	65.7483	0.309612	74.4937	0.342914	85.1451	0.428826
50.455	0.218012	54.818	0.299219	65.3606	0.307861	74.2137	0.342887	84.8086	0.427063

Table C.4. Composite pressure drop summary and statistical sampling for all tested BFEs (Continued).

Raw Composite Data Sampling for All Tested Filter Elements									
Flow Rate 1 (cfm)	Measured Pressure 1 (in H_2O)	Flow Rate 2 (cfm)	Measured Pressure 2 (in H_2O)	Flow Rate 3 (cfm)	Measured Pressure 3 (in H_2O)	Flow Rate 4 (cfm)	Measured Pressure 4 (in H_2O)	Flow Rate 5 (cfm)	Measured Pressure 5 (in H_2O)
50.2839	0.215033	54.5959	0.297898	65.3119	0.307547	74.0117	0.3413	84.5155	0.425623
50.3993	0.215166	54.7826	0.299661	65.1453	0.305389	74.0791	0.341548	84.9823	0.431787
50.1853	0.2282	55.2789	0.300329	64.9171	0.306974	73.4363	0.338504	84.6088	0.428868
49.8814	0.22553	55.2904	0.303434	65.0441	0.304184	73.8422	0.340713	85.1011	0.429604
49.327	0.222213	55.6097	0.303528	64.6347	0.3017	73.7493	0.339292	85.3813	0.430326
49.3284	0.222852	55.3805	0.30146	64.7475	0.305767	73.9541	0.339295	85.0283	0.508514
49.5226	0.223505	55.2136	0.302505	65.3227	0.307531	74.1097	0.342449	85.4371	0.512721
49.2525	0.223921	55.549	0.303839	65.2459	0.30733	73.6062	0.338179	84.5676	0.503468
49.3151	0.224398	55.3223	0.302918	65.3481	0.307746	73.7448	0.339124	85.0856	0.510269
49.3548	0.222704	54.9203	0.251328	65.5394	0.309091	74.5777	0.345545	84.9673	0.507423
49.422	0.224594	54.8393	0.249249	65.2552	0.3059	74.1726	0.342088	84.785	0.509511
49.4987	0.224432	55.0591	0.252699	65.2343	0.307797	74.1454	0.340555	84.6889	0.506939
49.2472	0.223362	55.1431	0.25122	65.4538	0.310767	74.904	0.346106	84.7103	0.502903
49.5858	0.225255	54.9525	0.252185	65.3874	0.308725	74.6478	0.34437	84.4339	0.503597
50.1248	0.227615	54.6057	0.248409	65.4727	0.30901	74.8706	0.34653	84.798	0.505753
50.013	0.228119	54.9551	0.250076	65.1885	0.306669	74.4753	0.343442	84.0151	0.501621
50.3237	0.229315	54.9627	0.250282	65.6281	0.310608	74.3696	0.343529	84.3602	0.502047
50.4351	0.229956	55.0482	0.25079	65.281	0.307125	74.6738	0.344635	84.8786	0.508034
50.2595	0.228759	54.8753	0.249294	64.9616	0.292358	74.9641	0.347753	85.1329	0.511394
50.2733	0.228108	55.2941	0.252231	64.6375	0.292435	75.0834	0.346335	84.7097	0.50595
50.3755	0.229238	55.159	0.251441	65.1394	0.294308	74.9916	0.345215	85.2448	0.508174
50.1945	0.227791	55.0646	0.251277	64.9982	0.292528	75.2218	0.346936	84.5242	0.50541
49.9549	0.22782	54.8643	0.249185	64.8621	0.291405	74.9606	0.344662	85.0261	0.510384
50.3055	0.230144	55.2997	0.253005	64.7561	0.292655	74.9458	0.346086	85.2133	0.507272
50.1123	0.226952	55.0624	0.250338	64.5321	0.289997	75.2896	0.348379	85.0716	0.424621
50.5739	0.229888	54.8729	0.250128	64.8135	0.292687	74.7925	0.344701	85.1952	0.427189
50.3297	0.229152	55.7611	0.253453	64.7623	0.29225	75.2888	0.347768	84.9305	0.421617
50.7347	0.270776	55.1393	0.242174	64.9224	0.291429	75.3058	0.34695	84.8039	0.424416
49.756	0.266132	55.0743	0.241893	64.7765	0.291939	75.0848	0.346564	85.2139	0.426056
49.6958	0.265878	54.8882	0.242558	64.9545	0.292056	75.3845	0.347915	85.3947	0.425195
49.2317	0.264829	54.7363	0.239814	64.9406	0.29236	75.0427	0.347102	85.4994	0.427608
49.1064	0.261877	54.6316	0.239946	64.7224	0.291198	74.6763	0.34536	85.1399	0.424849
49.3656	0.26422	54.5586	0.23914	64.7173	0.291404	74.8756	0.345282	85.6787	0.427629
49.5942	0.264441	54.7947	0.240253	65.0455	0.293058	74.9003	0.346156	85.1969	0.423618
49.303	0.263169	54.6889	0.239639	64.564	0.289803	75.4508	0.347731	85.136	0.425481
49.6053	0.265643	54.7527	0.239329	65.0521	0.293366	–	–	85.1892	0.426039
49.994	0.266465	54.7335	0.241043	64.9415	0.292258	–	–	85.3252	0.422674
49.8403	0.266759	55.1215	0.242136	64.793	0.29258	–	–	85.5331	0.427322
50.2013	0.268476	54.9107	0.241053	64.9238	0.292881	–	–	85.1189	0.425095
49.962	0.268286	54.7662	0.239487	64.7874	0.291476	–	–	84.6404	0.421634
49.9493	0.267947	54.8095	0.240316	64.7107	0.291788	–	–	85.2176	0.42599
49.958	0.267384	54.7149	0.240626	65.0418	0.293134	–	–	85.4075	0.426204
49.9922	0.26908	54.4533	0.238938	64.8698	0.294087	–	–	85.4494	0.427174
50.2775	0.269501	54.7494	0.239477	64.8242	0.292217	–	–	85.2734	0.424338
50.2646	0.270454	54.5803	0.237726	64.827	0.292033	–	–	85.4912	0.426062
49.8633	0.22381	54.7418	0.24032	64.7437	0.290441	–	–	85.2163	0.427374
50.1446	0.223737	54.6804	0.240432	64.8499	0.292732	–	–	85.5054	0.425848
49.5479	0.222431	54.7353	0.240952	65.0319	0.293225	–	–	85.5408	0.428072
50.1314	0.224485	54.8566	0.240596	65.0502	0.292545	–	–	85.4553	0.42628
49.8097	0.222786	55.1882	0.242545	64.6943	0.29058	–	–	84.7637	0.424775
49.9029	0.223449	54.4459	0.238937	64.7473	0.291997	–	–	85.5712	0.426464
49.9085	0.22354	54.7959	0.240771	64.727	0.290891	–	–	85.0535	0.422873

Table C.4. Composite pressure drop summary and statistical sampling for all tested BFEs (Continued).

Raw Composite Data Sampling for All Tested Filter Elements									
Flow Rate 1 (cfm)	Measured Pressure 1 (in H_2O)	Flow Rate 2 (cfm)	Measured Pressure 2 (in H_2O)	Flow Rate 3 (cfm)	Measured Pressure 3 (in H_2O)	Flow Rate 4 (cfm)	Measured Pressure 4 (in H_2O)	Flow Rate 5 (cfm)	Measured Pressure 5 (in H_2O)
50.1123	0.224369	54.9348	0.242087	64.6995	0.291621	–	–	84.8666	0.423714
50.1098	0.224295	55.0224	0.242472	64.8272	0.292685	–	–	85.0068	0.423559
49.9086	0.222777	54.6421	0.239659	64.9866	0.293702	–	–	84.7354	0.422684
49.9301	0.222699	–	–	64.8269	0.291948	–	–	84.6204	0.419279
49.829	0.223882	–	–	64.4261	0.290796	–	–	84.6622	0.4222
50.0754	0.22406	–	–	64.2444	0.289556	–	–	84.8876	0.424324
49.8925	0.223128	–	–	64.8885	0.293129	–	–	85.1365	0.421754
49.6561	0.222448	–	–	64.8555	0.291867	–	–	84.8217	0.425048
49.9389	0.222829	–	–	65.0595	0.2938	–	–	84.2827	0.418422
49.9589	0.22276	–	–	64.9484	0.292554	–	–	84.6605	0.420953
49.8556	0.223746	–	–	65.093	0.292607	–	–	84.9149	0.424582
49.8858	0.224095	–	–	65.0502	0.293602	–	–	85.0081	0.424707
49.7344	0.221982	–	–	64.7646	0.293173	–	–	85.0132	0.402572
49.8924	0.222942	–	–	65.05	0.293658	–	–	84.5165	0.398271
50.0693	0.224489	–	–	65.1698	0.293739	–	–	84.289	0.398155
49.9201	0.224299	–	–	65.0403	0.294021	–	–	84.7651	0.402339
50.4598	0.226095	–	–	64.9491	0.293519	–	–	84.5633	0.399686
50.6449	0.226763	–	–	64.7903	0.29265	–	–	84.9645	0.402859
50.3314	0.218807	–	–	65.0554	0.293329	–	–	84.6303	0.399338
50.6352	0.220158	–	–	–	–	–	–	84.4764	0.398884
50.7832	0.220397	–	–	–	–	–	–	84.8741	0.40059
50.0148	0.216989	–	–	–	–	–	–	84.647	0.400075
50.2124	0.218529	–	–	–	–	–	–	84.9891	0.402992
50.4221	0.218718	–	–	–	–	–	–	84.8545	0.401123
50.4729	0.218955	–	–	–	–	–	–	84.3756	0.399299
50.4805	0.218354	–	–	–	–	–	–	84.893	0.401569
50.292	0.217998	–	–	–	–	–	–	84.6893	0.401092
50.3311	0.218439	–	–	–	–	–	–	84.3308	0.39754
50.5377	0.218973	–	–	–	–	–	–	84.7259	0.399674
50.5701	0.22016	–	–	–	–	–	–	84.6143	0.399108
50.1721	0.215702	–	–	–	–	–	–	84.6514	0.401176
50.4805	0.218273	–	–	–	–	–	–	84.6646	0.399419
50.4286	0.218677	–	–	–	–	–	–	84.8095	0.400686
50.3503	0.218323	–	–	–	–	–	–	84.873	0.400761
49.9537	0.21753	–	–	–	–	–	–	–	–
50.69	0.219853	–	–	–	–	–	–	–	–
50.6719	0.219508	–	–	–	–	–	–	–	–
50.5327	0.21968	–	–	–	–	–	–	–	–
50.3983	0.218434	–	–	–	–	–	–	–	–
50.667	0.220752	–	–	–	–	–	–	–	–
50.3534	0.218496	–	–	–	–	–	–	–	–
50.2731	0.218599	–	–	–	–	–	–	–	–
50.4649	0.218557	–	–	–	–	–	–	–	–

APPENDIX D—CONSULTATION WITH MICROBIOLOGY SPECIALISTS

X-Sender: mmuil@hohp.harvard.edu (Unverified)
Date: Fri, 20 Dec 2002 14:03:32 -0500
To: Monsi Roman <monsi.roman@msfc.nasa.gov>
From: Mike Muilenberg <mmuil@hohp.harvard.edu>
Subject: HEPA filters

Hi Monsi:

Two days ago we discussed some issues with HEPA filters and microbial amplification and microbial particle release. At RH of 60% there is little or no chance of microbial amplification. There can be microclimate differences and therefore this must be qualified by saying that no amplification will occur as long as all parts of the filter and casing are at "room temperature" and at 60% RH. If there are cool spots, condensation can occur with resultant microbial growth.

As far as survival of organisms, the die off curve is pretty steep (even for Mycobacterium - as you saw in the paper by G. Ko). With continuous flow of (relatively) dry air, few bacteria will survive beyond a few days. There is always the cell or two (one hundredth of a percent of the total) that will survive longer. Even these shouldn't be a problem as they will be contained either on the HEPA filter until it is changed, or in the dust cake on the roughing filter until it is safely removed (using proper containment).

I talked with Steve Rudnick yesterday about the physical characteristics of HEPA filters. As long as dust removal (from the coarse filter) is well contained and the integrity of the HEPA filter is maintained (no physical damage and pressure drop within specifications), we don't see any reason why the life of the HEPA filters cannot continue to 2 years.

Hope this is helpful,
Mike

Re: FW: HEPA Filter Biologicals Buildup
From: Monsi Roman [monsi.roman@msfc.nasa.gov]
Sent: Friday, December 20, 2002 2:05 PM
To: Perry, Jay
Subject: Re: FW: HEPA Filter Biologicals Buildup

Jay,

As discussed with you before, I agree with the position of extending the life of the HEPA filters to 2 years. To back-up this position we can use the information in the paper from a research done at

Harvard School of Public Health- “Survival of Mycobacteria on HEPA Filter Bacteria” (1998 Journal of the American Biological Safety Association; authors: G. Ko, H. Burge, M. Muilenberg, S. Rudnick, M. First). I thought that this study has relevance because Mycobacteria are a relatively tolerant to environmental stress (pretty hardy bacteria), and it can be a problem in the hospital setting. Their data indicated that the potential of exposure to the viable cells during filter change-outs was minimal; cells were difficult to remove from filter material; less than 0.1% remained culturable after 48 hours; and exposure to re-aerosolized viable cells from disturbed HEPA filter material is unlikely. The study was performed using clean HEPA filters and accumulation of material on the surface of the filters can potentially protect bacteria- problems from debris accumulation are minimized by the periodic vacuuming of the filters.

I want to clarify that I am not saying, suggesting and/or implying in any way that we have Mycobacteria in the ISS (this is very important to understand!)--This information only gives us some reassurance that microbial survival on the filters should not be a problem.

In addition, I contacted Mike Muilenberg (School of Public Health, Harvard University) about the subject.

“Hi Monsi:

Two days ago we discussed some issues with HEPA filters and microbial amplification and microbial particle release. At RH of 60% there is little or no chance of microbial amplification. There can be microclimate differences and therefore this must be qualified by saying that no amplification will occur as long as all parts of the filter and casing are at “room temperature” and at 60% RH. If there are cool spots, condensation can occur with resultant microbial growth.

As far as survival of organisms, the die off curve is pretty steep (even for Mycobacterium - as you saw in the paper by G. Ko). With continuous flow of (relatively) dry air, few bacteria will survive beyond a few days. There is always the cell or two (one hundredth of a percent of the total) that will survive longer. Even these shouldn’t be a problem as they will be contained either on the HEPA filter until it is changed, or in the dust cake on the roughing filter until it is safely removed (using proper containment).

I talked with Steve Rudnick yesterday about the physical characteristics of HEPA filters. As long as dust removal (from the coarse filter) is well contained and the integrity of the HEPA filter is maintained (no physical damage and pressure drop within specifications), we don’t see any reason why the life of the HEPA filters cannot continue to 2 years.

Hope this is helpful,
Mike”

Please let me know if you need additional information,
Monsi

From: PIERSON, DUANE L. (JSC-SF) (NASA) [mailto:duane.l.pierson@nasa.gov]
Sent: Wednesday, December 11, 2002 8:27 AM
To: 'Thompson, Dean'; Perry, Jay; PERONNET, EDWARD H. (JSC-NE) (SAIC)
Cc: DECHOW, ROBERT W. (JSC-NE) (SAIC); MCCLELLAN, RUSSELL B. (JSC-NE) (SAIC); ROSE, MARY R. (JSC-NE) (SAIC); Barnes, Jeffrey E; Turner, Edward H; LEBLANC, STANFORD J. (STAN) (JSC-OE) (NASA); NGUYEN, HUNG X. (JSC-NE) (NASA); WILLIAMS, DAVE E. (JSC-EC6) (NASA); 'Gentry, Gregory J '; Turner, Edward H; LEWIS, JOHN F. (JSC-EC3) (NASA); PACKHAM, NIGEL (JSC-SF) (NASA)
Subject: RE: HEPA Filter Biologicals Buildup

Dean, rather than reiterate most of what Jay has said below, I can summarize by saying that I agree with Jay completely. The microbiological data obtained through the use of US provided CHeCS equipment (air and surface samplers) and the Russian provided monitoring equipment should NOT be used to determine when the BFE (HEPAs) should be changed. That should be assessed on ISS as it is done on the ground (e.g., microbiological hoods, etc.) by integrity checks and by measuring pressure drops. As long as the filter media has not been physically penetrated (very unlikely in ISS configuration) they typically last for long periods. Based on existing objective data, I see no microbiological reason why the service life of the BFEs can not be extended to two years. However, because the testing of the BFEs returned from ISS was conducted at MSFC, and given their responsibility in this area, it is important to obtain Monsi Roman's view on the subject and her approval (I assume this has already been done).

REFERENCES

1. Perry, J.L.: "Elements of Spacecraft Cabin Air Quality Control Design," *NASA/TP—1998–207978*, Marshall Space Flight Center, Huntsville, AL, May 1998.

2. "Airborne Particulate Matter in Spacecraft," *NASA Conference Publication 2499*, Washington, DC, 1988.

3. Wieland, P.O.: "Living Together in Space—The Design and Operation of the Life Support Systems on the *International Space Station,*" *NASA/TM—1998–206956*, Marshall Space Flight Center, Huntsville, AL, January 1998.

4. Liu, B.Y.H.; Rubow, K.L.; McMurry, P.H.; et al.: "Airborne Particulate Matter and Spacecraft Internal Environments," *SAE 911476,* 21st International Conference on Environmental Systems, Society of Automotive Engineers, Warrendale, PA, pp. 6, 10, July 1991.

5. Klusmier, L.: "THC—Bacteria Filter Contamination Study," *ANL 90–531,* Hamilton Sundstrand, Windsor Locks, CT, October 1990.

6. Klusmier, L.: "THC—Revised Bacteria Filter Contamination Study," *ANL 91–102*, Hamilton Sundstrand, Windsor Locks, CT, May 1991.

7. Turner, E.H.; and Gentry, G.J.: "Particulate and Microbe Removal Analysis Report for the *International Space Station* Stages 5A to 10A," *5–5352–ECLS–GJG–00–048,* The Boeing Company, Houston, TX, pp. 9–11, 25–32, December 2000.

8. von Jouanne, R.G.: "Requirement Closure Analysis for the USL PIDS Requirements for Filter Replacement," *D683–30032–4*, Sec. 134, The Boeing Company, Huntsville, AL, June 1999.

9. Ko, G.; Burge, H.A.; Muilenberg, M.; et al.: "Survival of Mycobacteria on HEPA Filter Material," *Journal of the American Biological Safety Association*, Vol. 3, No. 2, pp. 65–78, 1998.

10. Thompson, C.D.: "*ISS* ECLSS Expendables Service Life Improvements," *SAE 2003–01–2492*, 33rd International Conference on Environmental Systems, Vancouver, BC, Canada, July 2003.

11. Flaherty, C.J.: "Pricing Policy, Structure, and Schedule for U.S. Resources and Accommodations on the *International Space Station*," NASA Headquarters, February 11, 2000.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 2005	Technical Memorandum

4. TITLE AND SUBTITLE

International Space Station Bacteria Filter Element Service Life Evaluation

5. FUNDING NUMBERS

6. AUTHORS

J.L. Perry

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

8. PERFORMING ORGANIZATION REPORT NUMBER

M–1136

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPO NUMBER

NASA/TM—2005–213846

11. SUPPLEMENTARY NOTES

Prepared by the Spacecraft and Vehicle Systems Department, Engineering Directorate

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified-Unlimited
Subject Category 54
Availability: NASA CASI 301–621–0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The *International Space Station (ISS)* uses high-efficiency particulate air filters to remove particulate matter from the cabin atmosphere. Known as bacteria filter elements (BFEs), there are 13 elements deployed on board the *ISS*'s U.S. segment in the flight 4R assembly level. The preflight service life prediction of 1 yr for the BFEs is based upon engineering analysis of data collected during developmental testing that used a synthetic dust challenge. While this challenge is considered reasonable and conservative from a design perspective, an understanding of the actual filter loading is required to best manage the critical *ISS* program resources. Testing was conducted on BFEs returned from the *ISS* to refine the service life prediction. Results from this testing and implications to *ISS* resource management are provided.

14. SUBJECT TERMS

life support, particulate matter, HEPA filter, pressure drop, space station, ventilation, air quality

15. NUMBER OF PAGES

40

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

National Aeronautics and
Space Administration
IS04
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama
35812